2

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DIRECTIONAL THERMAL CONDUCTIVITIES OF GRAPHITE/EPOXY COMPOSITES: 0/90 and 0/±45/90

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This work and a predecessor investigation form a two-part experimental research program on the effective thermal conductivities of graphite-epoxy composites - the type which is used extensively in aerospace structures and other applications. Effective thermal conductivities were determined from 90°F to 250°F for composites with fibers arranged in the 0/90 and 0/±45/90 patterns. The fiber content was 60 % ~~percent~~ by volume. + or - Doc

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Analysis of the data in this work and the predecessor study established a correspondence principle between the directional effective conductivities of composites with uni-directional fibers and conductivities of other types of fiber arrangements. The correspondence principle allows an approximate but rapid estimate of the quasi-isotropic conductivities of the commonly used balanced-composites. Originator supplied keywords included: → front

FOREWORD

The research work contained in this report concludes a phase of investigation of the directional thermal conductivities of graphite/epoxy fibrous composites. Following a preceding experimental study of uni-directional fibrous composites, the present investigation undertook the measurement of the orthotropic conductivities of two types of graphite-epoxy composites, 0/90 and 0/±45/90 fibrous orientations, over a temperature range of 90°F to 250°F and for heat flow perpendicular to fibers and along the plies which made up the composite specimens.

The composite specimens tested in this study were fabricated in the Composites Facility of the Flight Dynamics Laboratory, (FDL) WPAFB, Ohio. Messrs. W. Yarcho, L. Mack, R. Zimmerman, and Ms. D. Oliveira were responsible for the timely completion of the specimen preparation. The work reported here was sponsored by the Structures and Dynamics Division, FDL, Mr. Nelson Wolf as the technical monitor. The authors of this report appreciate their support of the work, which began ~~May~~ JUNE 1983 and ended August 1984.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

NOMENCLATURE

C	specific heat
k	thermal conductivity
L	thickness of specimen block, see Figure 1
x	distance from the heating surface of Figure 1
T	temperature
Q	heat input to heater
α	thermal diffusivity
ρ	density
θ	time

Subscripts

e	effective value
x	transverse to plane of specimen, Figures 6 and 7
y	in-plane but transverse to fibers, Figures 6 and 7
z	in-plane and parallel to fibers, Figure 7
m	matrix or resin
∞	steady-state value
i	initial value
ip	in-plane direction
tr	transverse direction

I. INTRODUCTION

Although the importance of thermal analysis of composite structures in aerospace applications has long been recognized, it is only in recent years that experimental and analytical efforts have begun - judging from the accounts that appear in the literature and research reports. This trend is reflective, obviously, of the actual needs that arose, or of the anticipated requirements, forecast for various types of composites. Among the publications, there are more that are analytical than experimental. And in the experimental category, few deal with how thermal characteristics of composite materials come about, but more are concerned with test programs to meet thermal endurance requirements. These kinds of programs - in situ data collection and evaluation - are not amenable to generalization of the results. Nor can the data be reduced to a set of fundamentals in terms of the physical description of the constituents of the composites. It is the engineering fundamentals that are needed for rational analyses of the thermal properties of composites.

That these fundamental relations - conceptual or experimental - has become all the more important is demonstrated, for example, in assessing the thermal fatigue endurance of fibrous composites. Alternating heating and cooling on the surface of a composite body results in alternating thermal stresses, through the intermediate steps of temperature fluctuation in the interior of the body and thermal strains owing to different coefficients of thermal expansion for the two basic constituents of the media. From a calculational viewpoint what are needed specifically are:

the orthotropic conductivities of the composites and the fiber-matrix embedment geometry. A logical question can be raised: Can the directional thermal conductivities of a composite be reasonably predicted if the basic thermal prope :ies and the dispersion pattern of the fiber and the matrix material are known a priori?

As a first step to answer this question, the work of Han and Boyee [1] was undertaken. Graphite/epoxy with a 60 per cent fiber volume ratio, the kind used extensively in aerospace application, was fabricated in panels of 6x6 inches square, 0.5 inch thick. To render the situation simplified and controllable, graphite fibers were oriented in one direction only, by overlaying plies with prepregnated fibers in a same direction. Such a composite body has three principal axes: one transverse to both the fibers and the specimen plane; and the other two in the plane of the specimen, parallel to the fiber axis and perpendicular to it respectively. Determined in the preceding-mentioned work were the three principal effective conductivities of the composite and the isotropic conductivity of the re 'n material alone.

In reality of course, one-directional fibrous composites are not the exclusive one used. More commonly, composites with overlay patterns of 0/90 and 0/±45/90 are in contention, because of their "balanced" properties both mechanical and thermal. With regard to the thermal characteristics, one asks the questions: what are the principal effective thermal conductivities of these two types of composites, and how are the thermal conductivities of the composite as a whole related to, and predictable from the thermal conductivities of the constituents?

It follows naturally that this investigation being a sequel to [1] has the dual purposes of (i) establishing the principal effective thermal conductivies of the two balanced composites over a wider temperature range up to the glass/transition point of the resin-matrix and (ii) exploring the fundamental relationships between the thermal conductivities of the constituents (through the analytical studies previously completed) and the effective values of the composites.

The succeeding sections describe the research work accomplished.

II. THE EXPERIMENTS

2.1 The Experimental Apparatus.

The basic test scheme used is the same as that in an earlier work [1]. The main elements of the test assembly are depicted in Figure 1, which shows: (i) a central electric film heater* measuring 6x6 inches square and 0.007 inch thick overall. The thin foil heater is sandwiched between two 1/8-inch aluminum face sheets dissipating the heater input to both directions. (ii) At the two ends of the test assembly are two aluminum cooling plates which have built-in serpentine cooling water passages for cooling water circulation. (iii) Between the central heater and the two end cooling plates are placed two identical composite test specimen blocks, resulting in a symmetrical arrangement as shown in Figure 1. Such a configuration assures that the electric heater input is evenly divided to the two test specimen blocks. Naturally the peripheral surfaces surrounding the test assembly were insulated (Fiber-glas, 0.27 Btu-in/hr-°F-ft^2) during test runs to guard against side heat loss.

Cooling water was pumped to each cooling plate at a rate of 0.8 gallons/min from an elevated sump tank. Temperature of the cooling water was regulated by an immersion heater with variable power input. The tank, the cooling plate size and the coolant flow rate were ch that during a single test run lasting several hours, the cooling plate temperature remained unchanged.

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* Supplier: Electrofilm, Inc., Valencia, Cal., 10 watts/in^2.

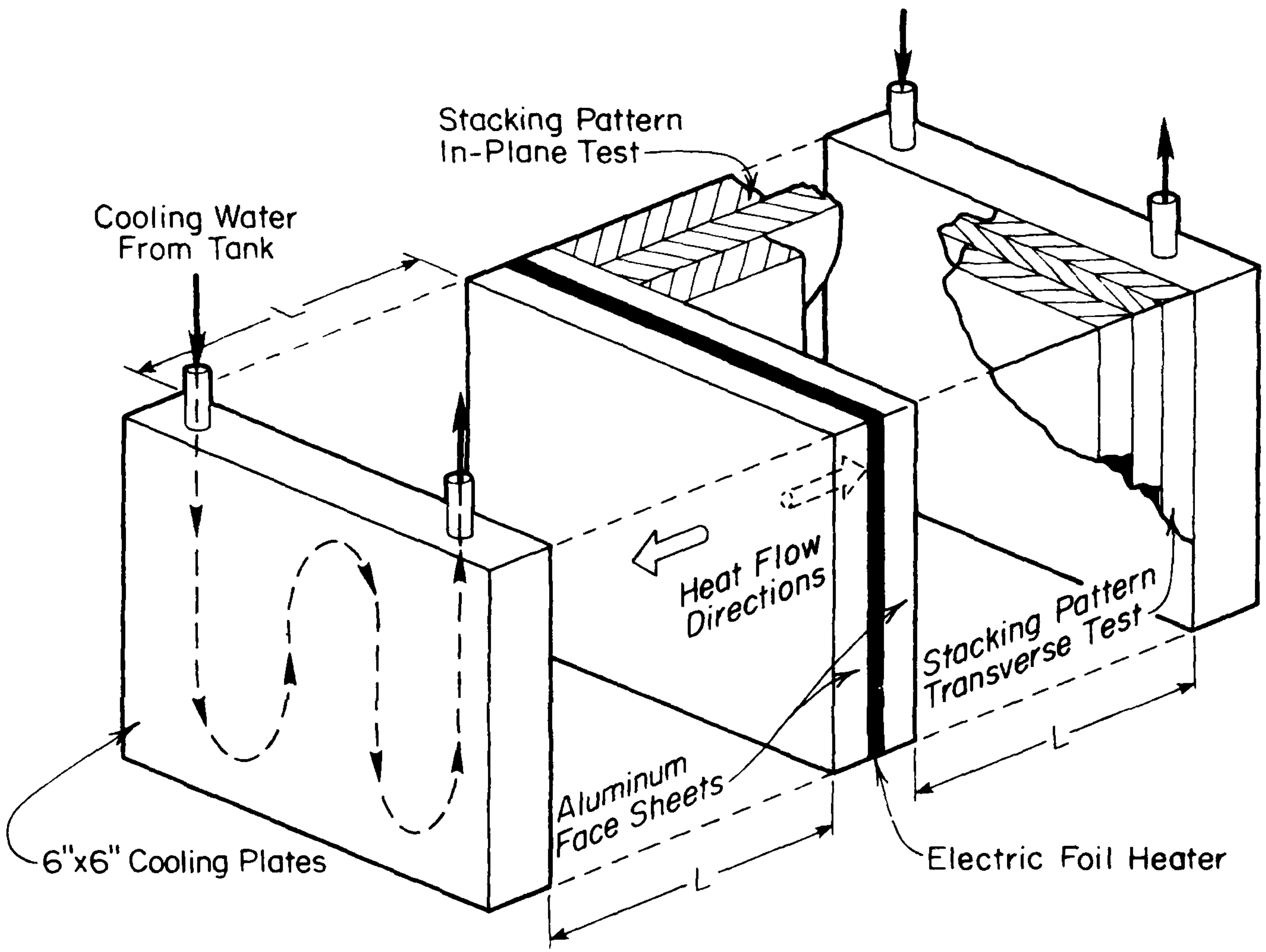

Figure 1. Schematic of Test Assembly.

Electric power input to the central film heater was supplied by a variable transformer with a rms voltage varying from 20 to 50 volts. The precise power input was measured by a direct rms voltage reading across the terminals of the electric film heater, which had an electric resistance of 38.2 ohms with virtually no drift during the entire experimental period. Symmetry of the geometrical arrangement assured symmetry of thermal consequence that the heat fluxes through the two specimen blocks are equal.

For temperature measurement, thermocouples (Iron-Constantan, type J, 30-gage) were located on the aluminum face plates of the heater assembly and the cooling plate surfaces at the ends of the test assembly. Within the test specimen block, thermocouples were installed so that temperatures could be measured along the heat flow axis from the heater to the cooling plate. Defining L as the heat flow distance and x=0 as the heater surface position, thermocouples were located at $x = L/6$, $L/2$ and $5L/6$. For heat flow tests transverse to the specimen (see Figure 1), thermocouples located at the centers of specimen panels were utilized. For heat flow tests in-plane of the specimen panels, a central-located panel with embedded thermocouples was used to extract the temperature readings. In all cases, 3/32-in grooves were provided for the thermocouple leads to come out of the test specimen blocks. Thermal grease - a paste with a high thermal conductivity - was used between two contact surfaces to minimize contact resistance; it was used only in the planes perpendicular to the principal heat flow direction. Used otherwise, it would constitute a heat flow short-circuit, thus voiding the test results.

2.2 The Test Specimens and Heat Conduction Modes

The specimens for thermal tests in this investigation were graphite-epoxy fibrous composites with a fiber content of around 60 per cent by volume. They were fabricated using commercially available Hercules AS-1/3502 low resin prepregs by the Structural Concepts Branch, Flight Dynamics Laboratory, WPAFB. The prepreg tapes or plies were of an average thickness of 0.0052 inches. Specimens with ply-arrangements of 0/90 and 0/±45/90 were prepared in 6x6 inches square panels with thickness of 0.29 in. for the 0/90 ply orientation and 0.507 in. for the latter. More details of their specifications are contained in Appendix A to this report, which is an excerpt from the descriptions of References [2] and [3].

The ply-fiber matrix relationships for the two types of composites are revealed in Figures 2 and 3, which are enlarged (400x) views of the cross-sections of these composites. Not only do they identify the stacking sequences of the plies for each type; but more than that, they show the dispersal patterns of the fibrous tows in each ply. Over the entire thickness of 0.0052 inches for one ply, there are about 15 rows of fibrous tows. Moreover, between two adjacent plies, there appears a border zone which is comprised of nearly all resin but no fibers - a fiberfree land, to paraphrase it. (Its significance will be discussed in connection with the experimental data.)

With that many rows of fibers in each ply, the mode of heat flow transverse to the plies is a succession of heat flow across these rows of cylindrical conductors or obstacles, as the case

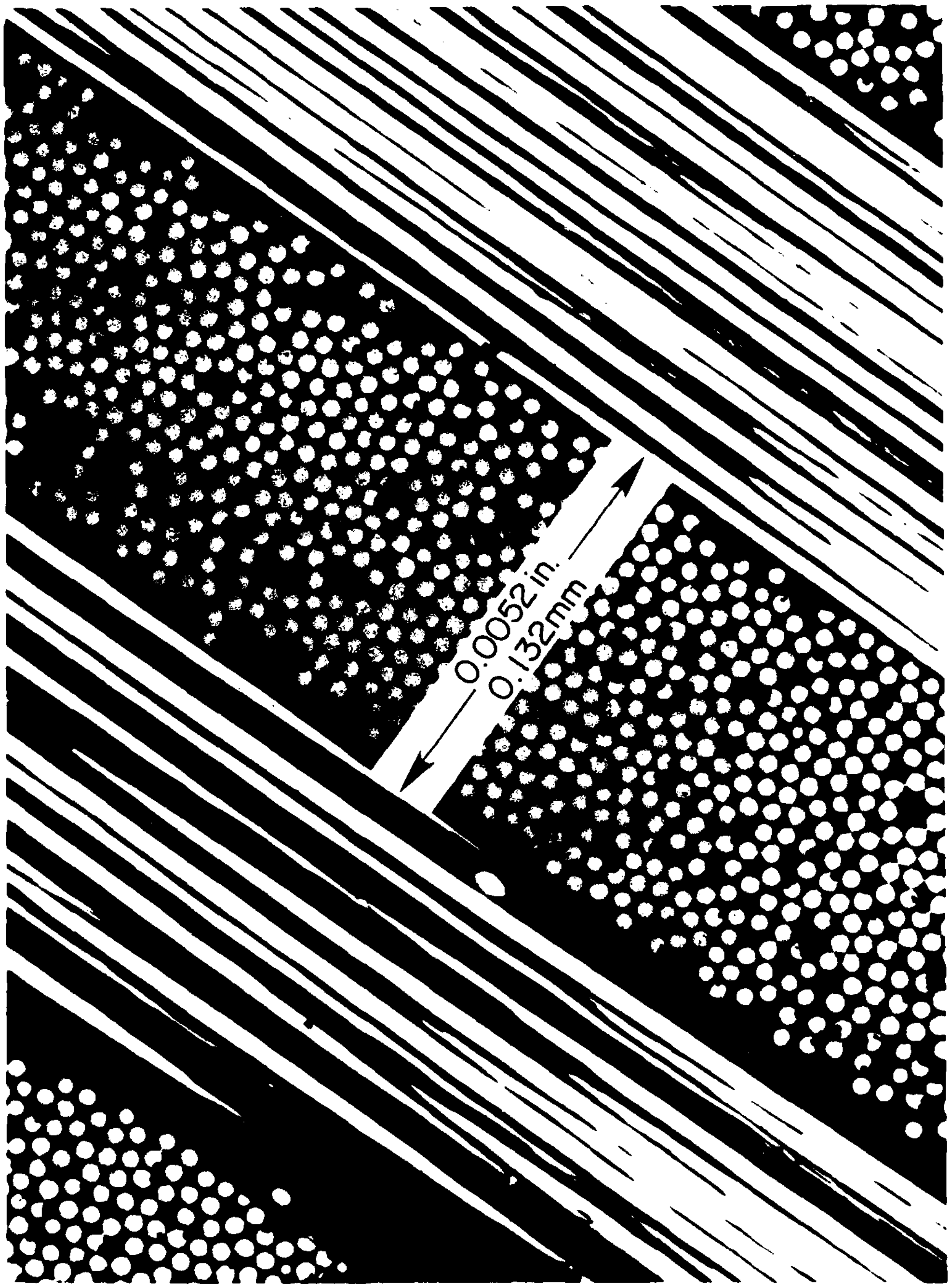

Figure 2. Enlarge Cross-Section (400x) of 0/90 Composite

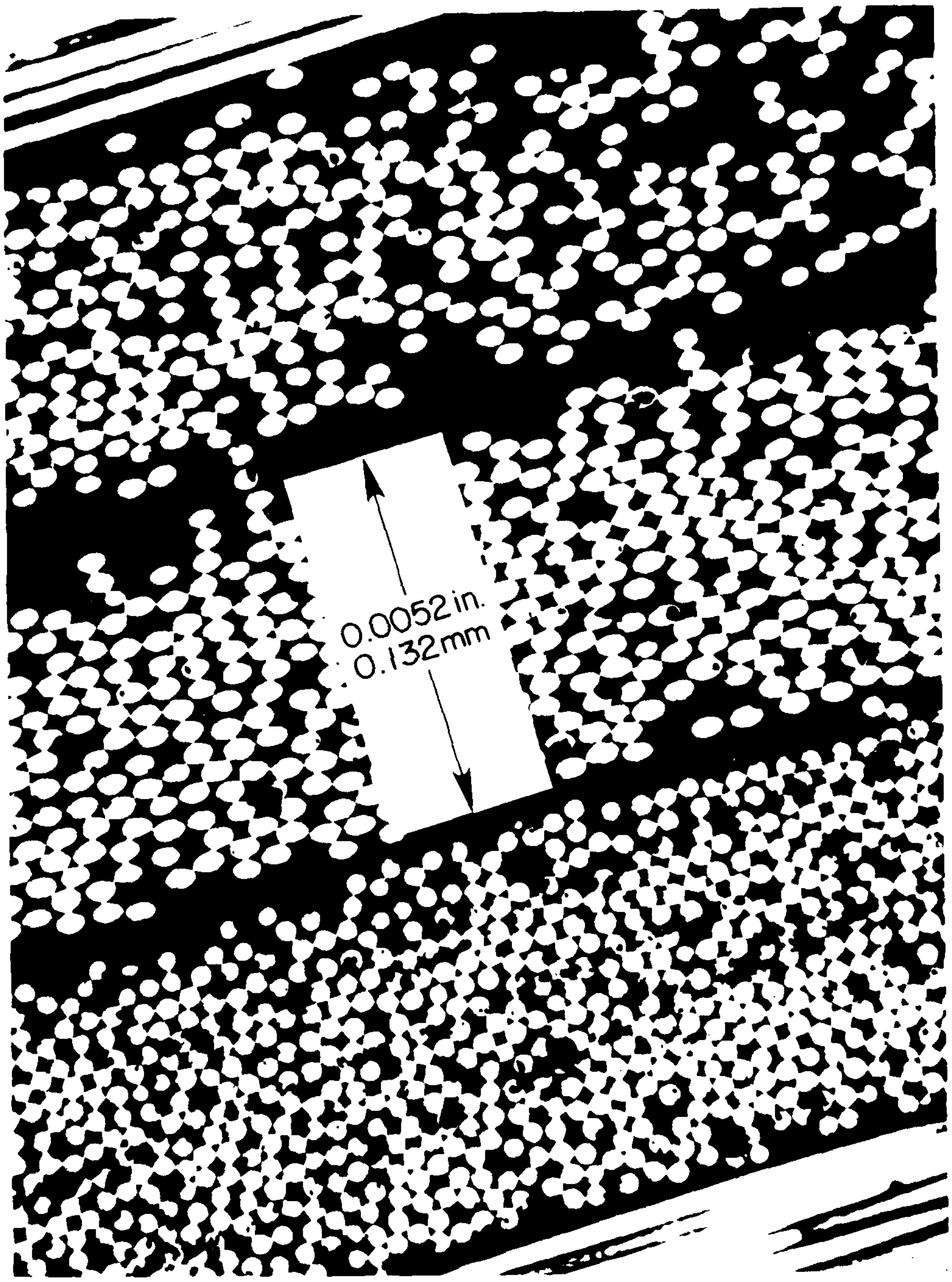

Figure 3. Enlarged Cross-Section (400x) of 0/±45/90 Composite

may be. In each ply, the heat flow pattern becomes rapidly established after encountering the first few rows. Hence it is not unreasonable to conclude that whether the plies are uni-directional, 0/90 or 0/±45/90, the modes of heat conduction perpendicular to the specimen plane are basically across the fiber-rows, but with interruptions to the orienting direction of the fibers after each group of 15 or so rows of fibers. These inter-ply disruptions modify somewhat, but hardly change the overall heat conduction patterns insofar as the entire specimen panel is concerned.

In variance from transverse conduction just described, heat conduction in the planes of the test specimen can be represented by summing up individual heat fluxes through each lamination or ply. For 0/90 composites, the fluxes are those along, and across the fiber axis in each ply. By virtue of symmetry, the effective in-plane conductivity is therefore independent of the heat flow direction and this is also true of the 0/±45/90 ply arrangement.

2.3 The Experimental Procedure

The general steps undertaken prior to an experimental run are: (i) checking the electric resistance of the electric film heater (38.2 ohms, stable throughout all runs), (ii) clamping the test assembly together by means of two head boards each facing an end cooling plate, with the head boards connected by four threaded steel rods, (iii) running cooling water from the tank at a pre-determined constant temperature through the end plates until the entire test assembly was at the same temperature as that of the cooling water - a step which usually took up from a few hours to a

day. The experimental run was then commenced by starting the electric heat input and recording the necessary temperatures of the test specimen blocks.

Voltage to the electric film heater ranged from 20 to 50 volts, regulated by a transformer. Temperature records were kept by feeding the thermocouple signals to a Data Logger. The one-dimensional nature of heat flow was confirmed by monitoring the temperatures on the specimen block, one inch on each side of the central heat flow axis of Figure 1. Their values compared with the temperature recorded on the central axis confirmed the one-dimensional nature. For each test run, the temperatures recorded were at the following five locations:

(i) $x=0$, the temperature of the heater surface in contact with the specimen block; thermal grease was used to ensure temperature equality.

(ii) $x=L/6$, where L is the space-length between the heater surface and the end cooling surface and is equal to the heat flow length across the specimen block. For in-plane conduction, the stacking patterns, as indicated in Figure 1, results in L=6 inch; for transverse conduction, the value of L varies. For the 0/90 plies, generally speaking, 18 panels of 0.29 inch thickness were used resulting in L=5.22 in. In the case of 0/±45/90 plies, 12 panels were used, giving L=6 inch for a panel thickness of 0.5 inches. For faster runs, 6 panels were used, with a correspondingly reduced value for L.

(iii) x=L/2, representing the mid-point location of the test specimen block.

(iv) x=5L/6, a position symmetrical to x=L/6.

(v) x=L, the surface temperature of the cooling plate.

A complete test run consumed as long as 10 hours. The conclusion of a run was established by noting the heater surface temperature variation until its fluctuation or change amounted to 0.1 per cent of the overall temperature gradient from the heater surface to the cooling surface.

The temperature at the five locations from x=0 to x=L when steady state was reached, plus the heater input voltage constituted the primary data source for evaluating the effective thermal conductivity for the test specimen block in the test assembly. The interior temperatures at x=L/6 and x=5L/6 were used to calculate the temperature gradient through the composite and one-half of the heater's electric input was the heat flow (steady state).

The procedure of data reduction and the method of extracting " C" from the transient test data are indicated in Appendix A to this report.

III. EXPERIMENTAL RESULTS

All together 39 heat conduction tests were performed on the two types of composite specimens: the 0/90 and 0/±45/90 graphite/epoxy combinations. The numbers of tests on each type are evenly divided; and for each type, there are two heat flow modes - transverse and parallel (in-plane) to the specimen panel, the number of test runs for each is about equal. Cooling water temperature in the supply tank was varied from 60°F to 200°F as a maximum. The heater surface temperature, which was partly influenced by the cooling water temperature, depended on the power input to the heater or the voltage imposed; the latter was varied from 20 to 50 volts. The resulting heater surface temperatures ranged from 120°F to 300°F, which, on account of a minimized contact resistance between the heater surface and the composite specimens by thermal grease, were also the high temperatures experienced by the composites. References [2] and [3] reported curing temperatures in the range of 350°F thereabout; it was felt safe to limit the maximum temperature below 350°F in order to prevent softening the resins in the composites.

For each conduction run, the effective thermal conductivity was calculated from the data at the steady state condition which consisted of the rms voltage to the heater, heating element resistance, and the five temperatures along the heat flow path. Based on the interior temperatures of the specimen block at $x = L/6$ and $x = 5L/6$, the temperature gradient was calculated, which, in conjunction with the power input, yielded the apparent or effective thermal conductivity. A sample of the complete set

of calculations is shown in Appendix A, including the method used to extract the thermal diffusivity from the transient temperature data.

For the runs conducted, principal results are listed in Tables 1 and 2 respectively for the transverse (perpendicular to specimen plane) and in-plane thermal conductivities. Further, in order to display their experimental scatter and temperature dependence, the data are graphically shown in Figure 4 for the transverse values, and Figure 5 for the in-plane conductivities. These two figures clearly demonstrate their relative magnitudes - the in-plane conductivity is about 4 or 5 times that of the transverse conductivity. Furthermore, the ratio of these two conductivities appears to be unaffected by whether it is a 0/90 composite or a 0/±45/90 composite; an interesting observation to be discussed later.

In addition to these characteristics, a notable feature is that as the temperature level increases the effective thermal conductivity also goes upward. Notwithstanding the paucity of supporting data, it can be plausibly explained that the increase in the effective conductivity, transverse or in-plane, is attributable to the increase of the thermal conductivity of the resin material in the composite. Recalling that for graphite fibers, a process temperature of 1000°C is normally employed; higher temperatures result in the so-called HM type and lower values give rise to the A-S type used in this investigation. Hence as the temperature level changes from 100 to 250°F, the variation is still quite remote from the temperature level at which the carbonization process or crystal re-alignment takes place. It is therefore not irrational to conclude that a change of temperature of 100 to 250°F hardly influences the thermal

conductivity of the fibers. On the contrary, the influence of this temperature change is sufficient to bring about a physical change in the resin and thereby raising its thermal conductivity, since the kind of resins used in the composites are known to have a curing temperature of 350°F approximately.

In addition to the effective conductivity, a companion result of this work is the thermal diffusivity, a property essential in transient thermal analysis. The transient temperature records obtained in the conduction tests were synthesized - albeit without great precision - to estimate the diffusivity values of the composite. The synthesis procedure is based on a least-square fit with the predicted temperature history of the midpoint in the test block. The "estimated" data for the specific heat of the composites are shown in Figure A-3; and since the method has yet to be refined, the data are to be considered provisional.

Table 1. Effective Transverse Conductivity Data

Run No.	T_{av} °F	ΔT °F	Q Watts	dT/dx °F/in	k_{tr} $\frac{Btu}{(hr-°F-ft)}$	$\alpha 10^5$ ft^2/sec	L in.
(0/90) Composites; 18 panels, each 0.29 in. thick							
612	191	46	10.4	13.0	0.441	0.180	5.22
619	186	68	13.7	17.8	0.439	0.254	5.22
620	186	68	13.8	18.1	0.435	0.273	5.22
611	100	56	9.45	13.6	0.395	0.375	5.22
618	109	63	10.9	15.0	0.413	0.380	5.22
626	126	104	17.7	24.2	0.416	0.400	5.22
627	120	70	12.7	16.5	0.437	0.380	5.22
628	112	68	9.75	15.8	0.352	0.360	5.22
606	93	42	17.4	24.1	0.410		1.74
605	190	70	33.9	40.4	0.477		1.74
(0/±45/90) Composites; 8 panels each 0.507 in. thick.							
508	154	101	29.9	32.8	0.519	0.450	3.04
510	187	76	24.8	24.8	0.569	0.400	3.04
515	184	75	23.9	24.6	0.553	0.380	3.04
517	181	73	23.4	23.9	0.556	0.380	3.04
426	116	82	22.3	26.9	0.471	0.425	3.04
501	105	61	17.2	20.2	0.484	0.460	3.04
503	110	65	17.7	21.4	0.469	0.460	3.04

T_{av} is the average of the heater surface and cooling plate surface temperatures, ΔT is their difference.

Table 2. Effective In-Plane Conductivity Data

Run No.	T_{av} °F	ΔT °F	Q Watts	dT/dx °F/in	k_{ip} $\frac{Btu}{(hr-°F-ft)}$	$\alpha 10^5$ ft^2/sec
(0/90) Composites: L = 6.00 in.						
718	247	104	70.8	16.6	2.516	2.00
719	254	99	68.1	16.1	2.488	2.00
723	245	100	68.1	16.1	2.488	2.20
209	189	124	70.8	20.8	2.006	2.12
214	197	115	73.0	19.2	2.230	2.00
216	198	118	71.9	19.5	2.170	2.00
703	106	63	35.6	10.7	1.963	1.90
706	109	59	33.9	10.0	1.991	2.23
709	108	60	33.9	10.1	1.981	2.23
(0/±45/90) Composites, L = 6.00 in.						
724	234	80	60.3	13.1	2.587	1.71
725	251	94	70.8	15.5	2.565	1.74
726	246	99	73.5	16.3	2.530	1.75
727	239	94	70.8	15.6	2.553	1.80
524	165	37	26.3	6.15	2.399	1.92
529	172	35	25.6	5.88	2.448	2.00
530	165	50	33.6	8.25	2.280	2.00
531	182	82	56.4	13.7	2.312	2.25
412	85	30	18.0	4.80	2.100	2.25
419	102	58	36.2	9.48	2.144	2.00
422	104	60	37.4	9.55	2.196	2.20
621	90	16	9.6	2.58	2.080	2.08
625	85	19	13.8	3.78	2.058	2.00

T_{av} is the average of the heater surface and cooling plate surface temperatures, ΔT is their difference.

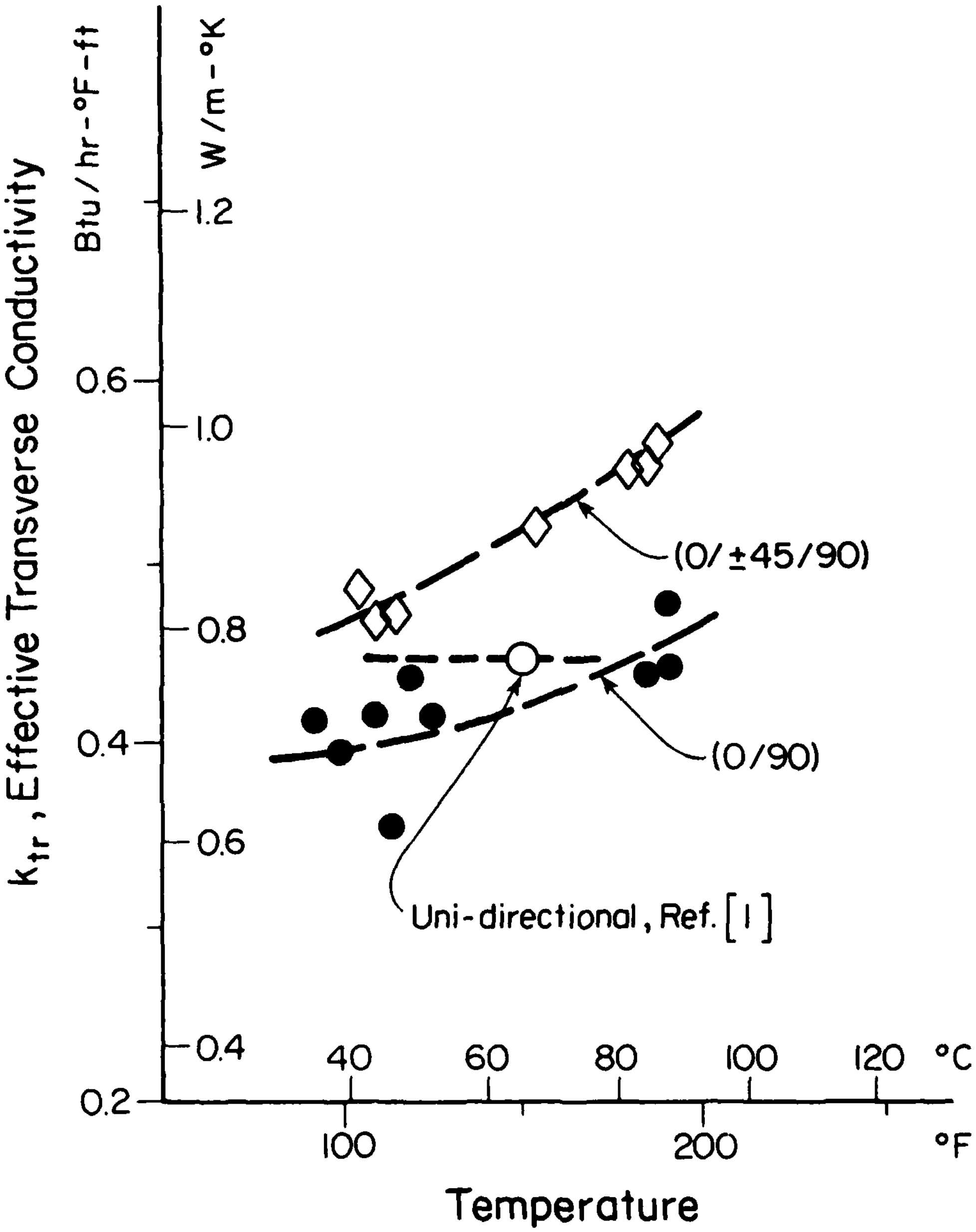

Figure 4. Effective Transverse Conductivities of Graphite/Epoxy Composites, Fiber Volume Ratio = 60 Per Cent.

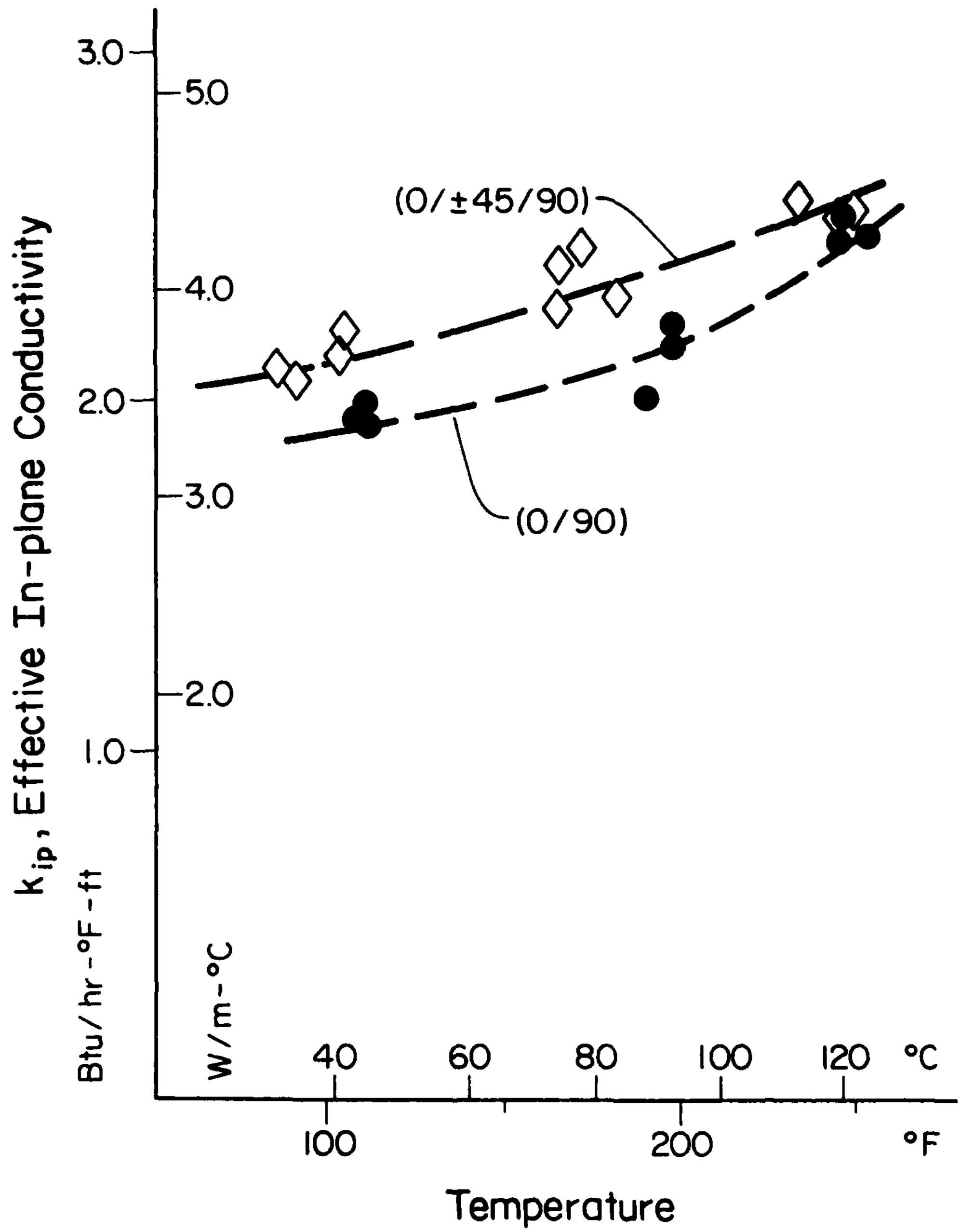

Figure 5. Effective In-plane Conductivities of Graphite/Epoxy Composites, Fiber Volume Ratio = 60 Per Cent.

IV. ANALYSIS OF THE EXPERIMENTAL DATA

1. Composites with Uni-Directional Fibers

The predecessor investigation, that of Reference [1], undertook the measurement of three principal effective thermal conductivities for graphite-epoxy composites with uni-directional fibers. The constituent materials - the prepreg plies and the resins - were the same as used in this investigation for 0/90 and 0/±45/90 composites. Thus, a re-examination of the uni-directional data would lead to a rationalization of the data obtained in this study. The principal results of [1] can be summarized as follows:

Effective Thermal Conductivity, Btu/hr-°F-ft

k_{e-x} (transverse to fibers and to plane) = 0.448

k_{e-y} (transverse to fibers and in-plane) = 0.645

k_{e-z} (parallel to fibers and in-plane) = 3.63

Epoxy Thermal Conductivity

k_m = 0.136

Figure 6 clarifies the above description. The value for the epoxy thermal conductivity is in agreement with that in Reference [5].

From the effective conductivity parallel to the fiber axis, and based on the fiber fraction of 0.597 by volume, Reference [1] deduced a thermal conductivity value of 5.99 Btu/hr-°F-ft for the fiber constituent. For graphite fibers of the AS-type, Reference [4] lists a value of 5.0

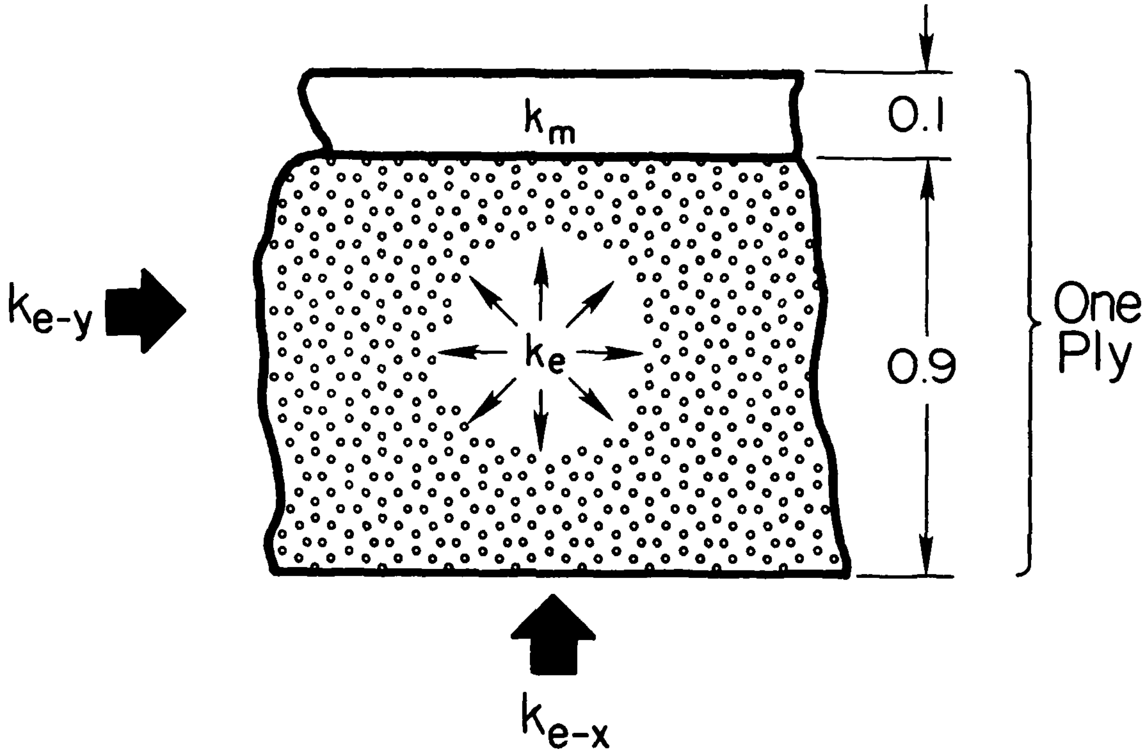

Figure 6. Schematic of the Principal Effective Conductivities of Uni-directional Composites

Btu/hr-°F-ft, so the value determined in Reference [1] is consistent and reasonable.

The other two principal effective conductivities - both for heat flow across the fiber axis - are interesting to analyze. In order to understand how these two different values came about, examination of the cross-sections of the uni-directional composites indicates that there exists a boundary zone between two plies which is almost free from fibers. Figures 2 and 3, though taken with 0/90 and 0/±45/90 overlay patterns, indicate such a phenomenon. It is estimated from these pictures that the width of the fiber-free canals, which is in reality formed by the surface coating of the prepreg tapes, is approximately 0.1 of the ply thickness. In the remaining space of the ply, the fibers appear to be well dispersed, although not uniformly throughout.

This observation leads to the interpretation of the two heat conduction modes: when heat conduction is transverse to the specimen plane, i.e. transverse to the plies, it penetrates in series the main region with well-dispersed fibers and the fiber-free boundary zone. For heat conduction in the plane of the specimen but still perpendicular to the fibers, there are two heat fluxes in parallel: - one in the fiber-free boundary zone and the other in the mixed region where both constituents are present. Figure 6 illustrates these two different heat conduction modes in these two directions. Let k_e and k_m be the (isotropic) conductivities of the mixed region and the boundary zone. The latter is of course the same as the resin conductivity. The apparent or measured effective conductivities k_{e-x} and k_{e-y} must be related to the intrinsic quantities of k_e and k_m as follows:

$$k_{e-y} = 0.1\, k_m + 0.9\, k_e$$
$$k_{e-x} = k_m k_e/(0.9k_m + 0.1k_e)$$

With k_f and k_m known as 5.99 and 0.136 Btu/(hr-°F-ft), and with the dispersed pattern of the fibers in the resin matrix to be closely approximated by a hexagonal pattern, the effective thermal conductivity k_e of the mixed region was obtained by the method of Reference [5].

Procedurally, the steps consisted of calculating the ratio of fiber-to-matrix conductivities (5.99/.136 = 44); introducing this ratio to one of the performance charts in Reference [5], in this case Figure 11 of that reference for a volume ratio of 0.7; and obtaining the resulting ratio (k_e/k_m) for an angle factor 30°. These steps give an effective conductivity of k_e = 5 x .136 = 0.68 Btu/f(hr-°F-ft). The directional effective conductivities k_{e-y} and k_{e-x} can then be calculated from the two equations given above; they are

$$k_{e-y} = 0.626 \text{ Btu/(hr-°F-ft)}$$
$$k_{e-x} = 0.486 \text{ Btu/(hr-°F-ft)}$$

Experimentally they turned out to be 0.645 and 0.448 respectively. The discrepancy is obviously multi-faceted and hinges on how well the extent of the fiber-free border layer is estimated. Nonetheless the zonal structure of the fibrous matrix leading to directional-dependent effective conductivities appears to be quite convincing, in view of the values so analyzed.

2. Composites with 0/90 Overlay Pattern

The enlarged views of the fiber dispersion patterns of the 0/90 and 0/±45/90 overlays shown in Figures 2 and 3 indicate that insofar as heat conduction in the transverse (to the specimen plane) is concerned, very little differentiation exists between all three fiber orientations. All three modes of heat conduction pass through a large number of fiber rows - approximately 15 rows per ply; for the 0/90 and 0/±45/90 overlays, the tapes change their orientation, but not the relative direction between the fiber rows and the heat flow. Consequently for heat flow perpendicular to the specimen plane, all three configurations should exhibit effective conductivities close to one another. Data in Figure 4 indicate a mean transverse conductivity of 0.42 Btu/hr-°F-ft for the 0/90 pattern for a temperature range of 90°F to 200°F. For the 0/±45/90 fiber orientation, a mean value of 0.51 was found. Compared to 0.448 for the uni-directional composites, the transverse conductivity appears to be relatively unaffected by the fiber arrangement.

With regard to the effective in-plane thermal conductivity, its value for the 0/90-arrangement ranges from 1.95 at 110°F to 2.50 at 250°F in units of Btu/(hr-°F-ft). These values can be synthesized by considering the overlay geometry shown in Figure 2. Heat conduction in the plane of the specimen is comprised, therefore, of parallel flows across the fibers in one ply, but along the fibers in the next ply, and so on. In other words, the effective in-plane thermal conductivity can be deduced by averaging the two in-plane effective conductivities of composites with uni-directional fibers. For the latter, values of 0.645 and 3.63 were

obtained in Reference [1]; and based on these, effective in-plane thermal conductivity of 2.14 Btu/hr-°F-ft should be expected. Inspection of the data in Figure 5 bears out this expectation.

Another source of correlation or corroboration is found in an analysis of Reference [5], in which the heat conduction pattern was studied for a configuration consisting of a large number of rows of cylindrical fibers with a succeeding row at 90° from the preceding one. In other words, the geometrical pattern is similar to Figure 2, except that there is but one fiber across the entire thickness of the ply.

Figures 13 and 14 of Reference [5] are pertinent in this regard; the former is for heat conduction tranverse to all fibers, i.e., transverse to the specimen plane and the latter is for transverse-axial heat flow, i.e. along the axis of one row of fibers but transverse to it in the next row - the in-plane conduction mode for the 0/90 equivalent. For a volume ratio of 0.6, very nearly correct for the specimens used in this investigation, and for a (k_f/k_m) ratio of 44.0, Figures 13 and 14 of Reference [5] give the following two ratios

$$(k_e/k_m), \text{ transverse to plane} = 3.7$$
$$(k_e/k_m), \text{ in-plane} = 17.5$$

For $k_m = 0.136$, these two ratios correspond to $k_{e-x} = 0.503$ and $k_{e-y} = 2.38$ Btu/(hr-°F-ft), which are quite consistent and in fair agreement with the measured values of this experimental work.

3. Composites with 0/±45/90 Overlay Patterns.

The pattern of the overlaying plies is literally indicative of the designation and is shown geometrically in Figure 3. The fiber orientation of the four plies are arranged from the first ply at zero degree from the horizontal axis and at different angles for the succeeding plies. For a repeating pattern of the four plies, the arrangement is therefore:

$$0/+45/-45/90$$

Such a ply overlay pattern matters very little insofar as heat conduction across the specimen plane is concerned, and the effective transverse thermal conductivity should be very near that of 0/90 or uni-directional composites. It is indeed the case, as the data in Figure 4 so indicate.

For the effective in-plane conductivity, heat flow consists of four parallel paths: along the 0-degree ply - the axial flow along the fibers; along the 90°-ply -- the transverse flow across the fibers; and two identical heat flow paths along and across the 45-degree inclined fibers. For the first two heat paths, their combined contribution to the in-plane value is one quarter of the values of k_{e-y} and k_{e-z} for uni-directional fibers. For the 45-degree plies, each may be considered to possess an equivalent conductivity which is the average of the axial and transverse values, i.e., k_{e-z} and k_{e-y}. This is by necessity a very simplified picture. Although a more elaborate analysis along the line of an-isotropic heat flow (see Reference [6]) may be undertaken, but the resulting

modification is judged to be very minor. Hence the effective in-plane thermal conductivity for the 0/±45/90 ply arrangement ought to differ but very little from the 0/90 arrangement. Experimental data shown in Figure 5 for these two ply-patterns confirm this deduction.

V. CONCLUSIONS

(i) Shown in Figures 4 and 5 are the quasi-isotropic effective thermal conductivities for graphite/epoxy composites with 0/90 and 0/±45/90 ply arrangements. The data are self-evident and no further elaborations are necessary.

(ii) Analysis of the data and consideration of the heat conduction patterns in the uni-directional fibrous composites led to some approximate but simple relations between the quasi-isotropic conductivities of the two types with the orthotropic conductivities of the uni-directional composites. The relations are depicted in Figure 7, in which Part (a) shows the three principal effective conductivities for the uni-directional composites: k_{e-x}, k_{e-y}, and k_{e-z}. Part (b) illustrates the notations for the 0/90 ply orientation but is also valid for the 0/±45/90 pattern. The correspondence relations are:

$$k_{tr} = k_{e-x}$$
$$k_{ip} = (k_{e-y} + k_{e-z})/2$$

Stated explicitly: The effective conductivities transverse to all fibers are virtually unchanged by the fiber arrangement pattern - uni-directional, 0/90 or 0/±45/90. For the latter two types, the in-plane (quasi-isotropic) conductivity k_{ip} is approximately the average of the two in-plane effective orthotropic conductivities of the uni-directional composite.

These relationships -- though only approximate in nature -- can give an estimate of the quasi-isotropic conductivities in rapid order and in that sense are quite useful.

To implement the above-stated correspondence principle, three effective principal conductivities are required for the uni-directional fibrous composite. These three conductivities can be obtained either by an analytical procedure following the outline of Reference [5] or some other method; alternately and more reliably, uni-directional fibrous composites specimens may be tested for their effective conductivities. If analytical procedures are followed, the primary input values are the constituents' thermal conductivities -- fibers and resin -- and their volume fraction. The ratio of fiber-to-resin thermal conductivities in conjunction with the fiber volume fraction gives the ratio of the effective-to-resin conductivities for the transverse direction.

Although there are numerous analog-based formulas available, the analysis in Reference [5] -- which is exact mathematically -- can be used with confidence. The result of Reference [5] indicates that the ratio k_e/k_m (transverse effective to resin) is dependent on the ratio k_f/k_m. Furthermore, a change of the latter brings about a change of the former only in the range of k_f/k_m below 20; above this value, the ratio k_e/k_m tends to approach a constant asymptotic value.

(iii) In the course of experimentation, the transient heat conduction technique was shown to be also of value in obtaining data for thermal

diffusivity. For the types of composites investigated, the specific heats are shown in Figure A-3 as provisional data. Further refinements in the instrumentation would lead to more reliable results.

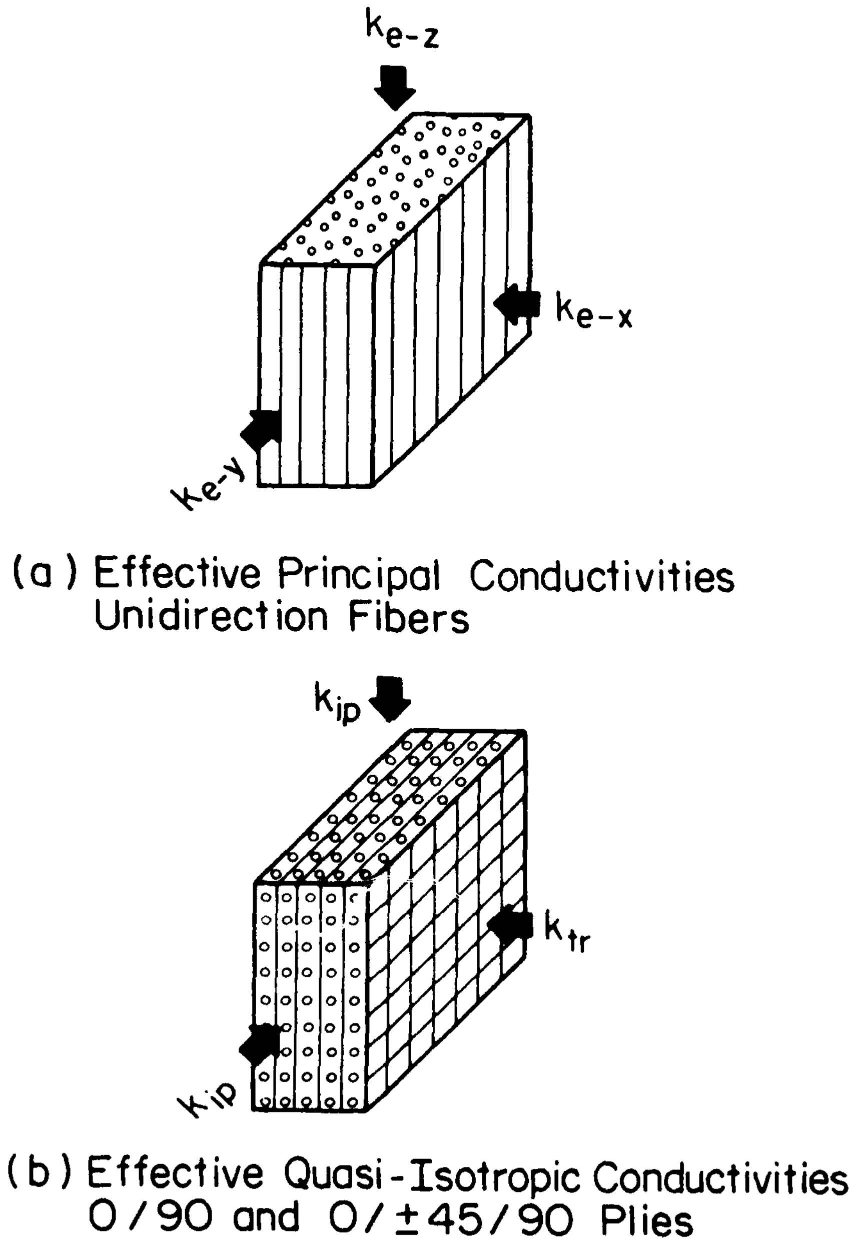

Figure 7. Correspondence Relations of Effective Quasi-Isotropic Conductivities

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APPENDIX A PROVISIONAL SPECIFIC HEAT DATA AND SAMPLE OF DATA ANALYSIS

Effective Thermal Conductivity

To illustrate the method of analyzing the recorded data from a typical heat conduction experiment, a step-by-step description is given here. Table A-1 contains temperature-time histories of the heating surface, three interior points in the specimen block and the cooling surface at the end. The test specimen block consisted of six 0.507-in thick panels of 0/±45/90 composite and had an overall thickness of 3.042 in (L = 6x.507).

Initially, the entire test assembly including the heater assembly and the test blocks was brought to the cooling water temperature of T_i = 75.3°F, at which the cooling water was maintained throughout the test run. An input of 29.2 volts was started through the electric film heater and the power input was 22.3 watts. Aside from the sensible heat absorption of the heater itself and the aluminum face sheets, the process was nearly one of constant heat flux. At θ_∞ = 20460 seconds, steady-state was essentially established at which time the heater surface temperature was 157.1°F with a less than 0.1°F fluctuation.

To compute the effective thermal conductivity, the temperature gradient was obtained on the basis of the two extreme interior temperature values, (although the gradient based on the heater and cooling surface temperatures was not much different.) The gradients of these two different sources were illustrated in Figure A-1. Using 22.3 watts for heat input to the test specimen block, and for a conduction area of 6x6 inches square, an effective thermal conductivity of 0.471 Btu/(hr-°F-ft) was obtained for a mean temperature of (157+75)/2 = 116°F.

Effective Thermal Diffusivity

While the primary purpose of this investigation was focused on the thermal conductivity of the composites, the experimental data obtained were also utilized to estimate the thermal diffusivity of the composites undergoing test. If the method of obtaining diffusivity data can be reasonably established and refined, it affords a convenient way of getting thermal conductivity and diffusivity data simultaneously.

The conceptual base for such a methodology is the solution of one-dimensional transient heat diffusion equation for a region bounded by two surfaces at which the temperature variations are known. The solution, which contains the thermal diffusivity of the material, can be used to calculate the temperature-time history of any interior point. The experimental data for the heating and cooling surface supply the necessary boundary conditions at $x = 0$ and $x = L$, between which the transient solution applies. Since the interior temperature variations are known from the measured values, the thermal diffusivity can in principle be inferred directly. That is, by assuming a succession of numerical values for the thermal diffusivities, there ensue a succession of temperature-time histories at, say $x = L/2$. The one which matches the experimentally-determined variation best is the one that represents the best value for the thermal diffusivity. Instead of a direct match, the criterion of a least-squares fit is adopted between the time limits from a time when the mid-point ($x=L/2$) temperature rise is at 10 per cent of the asymptotic temperature change to the time when the rise is at 90 per cent of the steady-state value. Between the time limits, the least-square error between the calculated temperatures of the mid-point and the experimental data determines the best thermal diffusivity value.

For the data in Table A-1, the temperatures T_1 and T_5 are the input boundary conditions. Using the procedure just described, a diffusivity value of $\alpha = 0.475 \times 10^{-5}$ ft²/sec was obtained. At this value, the calculated temperature profiles for T_2, T_3, and T_4 are shown in Figure A-2, which also contains the measured variations (solid lines). For the 0/90 and 0/±45/90 composites used in this investigation, an average density of ρ = 100.2 lb/ft³ was given by the manufacturer's data. From the effective thermal conductivity k_e = 0.471 Btu/hr-°F-ft, and the least-square thermal diffusivity $\alpha = 0.475 \times 10^{-5}$ ft²/sec, specific heat can be calculated; this results in C = 0.275 Btu/lb-°F or cal/gm-°C.

It should be emphasized that the method of least-squares in "matching" the experimental curve with the calculated one is not sufficiently precise at this stage or with the simple instrumentation used in this study. The numerical values of the specific heat for the composites thus determined are, however, in fair agreement with the data found in Reference [7] for similar types of composites. The specific heat data shown in Figure A-3 must, therefore, be considered provisional, pending further confirmation or refinement.

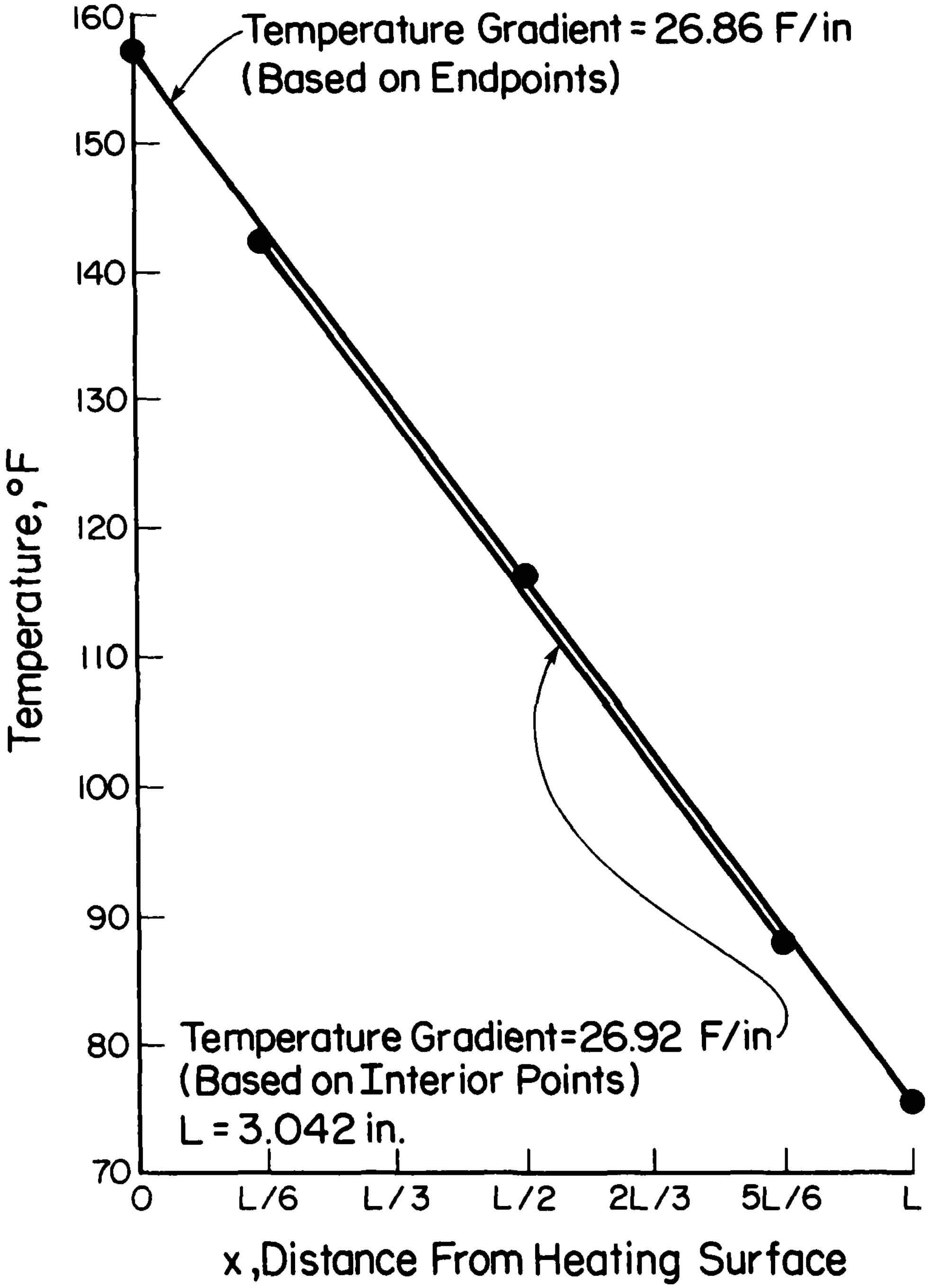

Figure A.1 Steady-State Temperature Profiles in Test Specimen Block

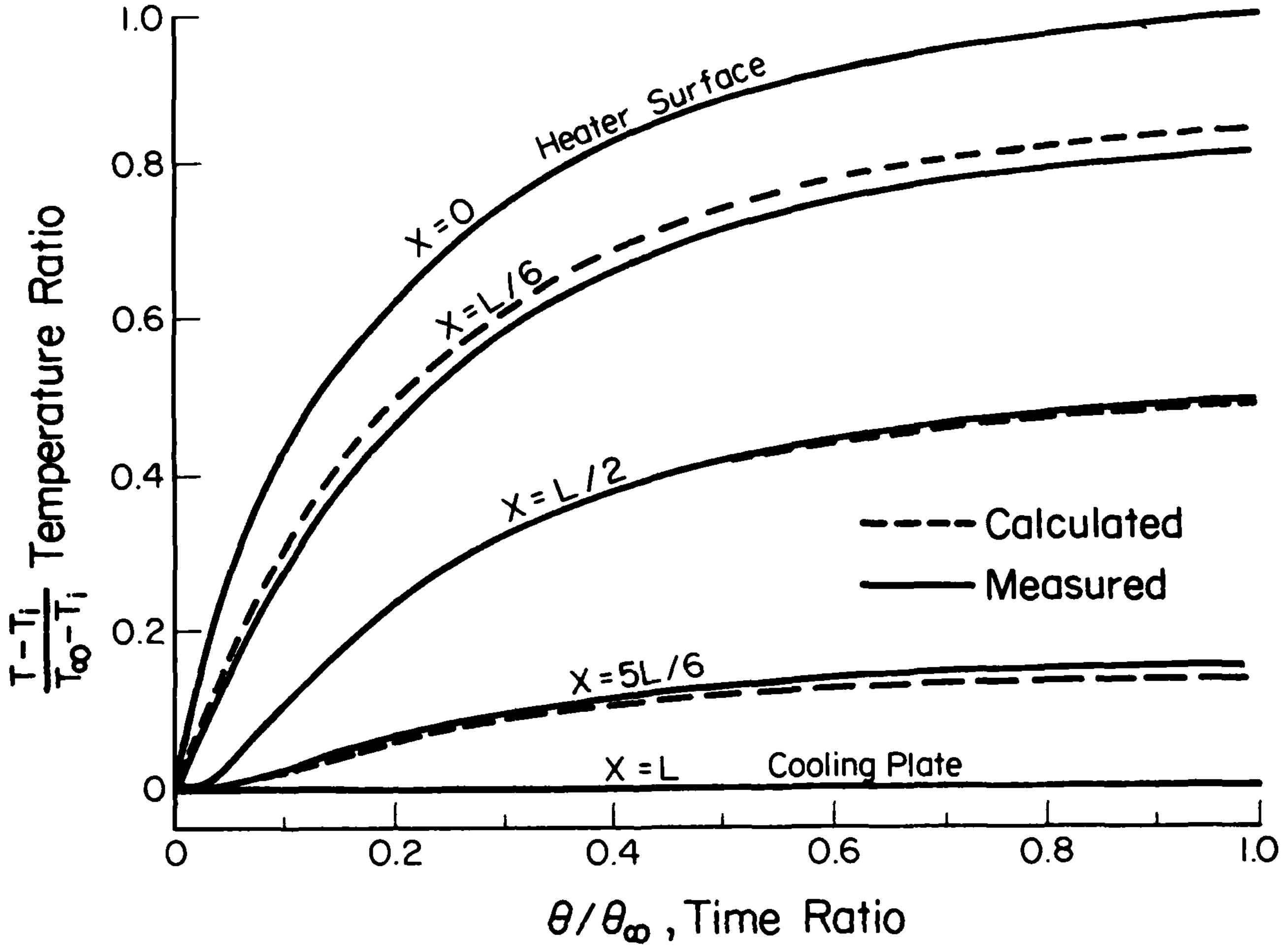

Figure A.2 Temperature-Time Histories in Test Specimen

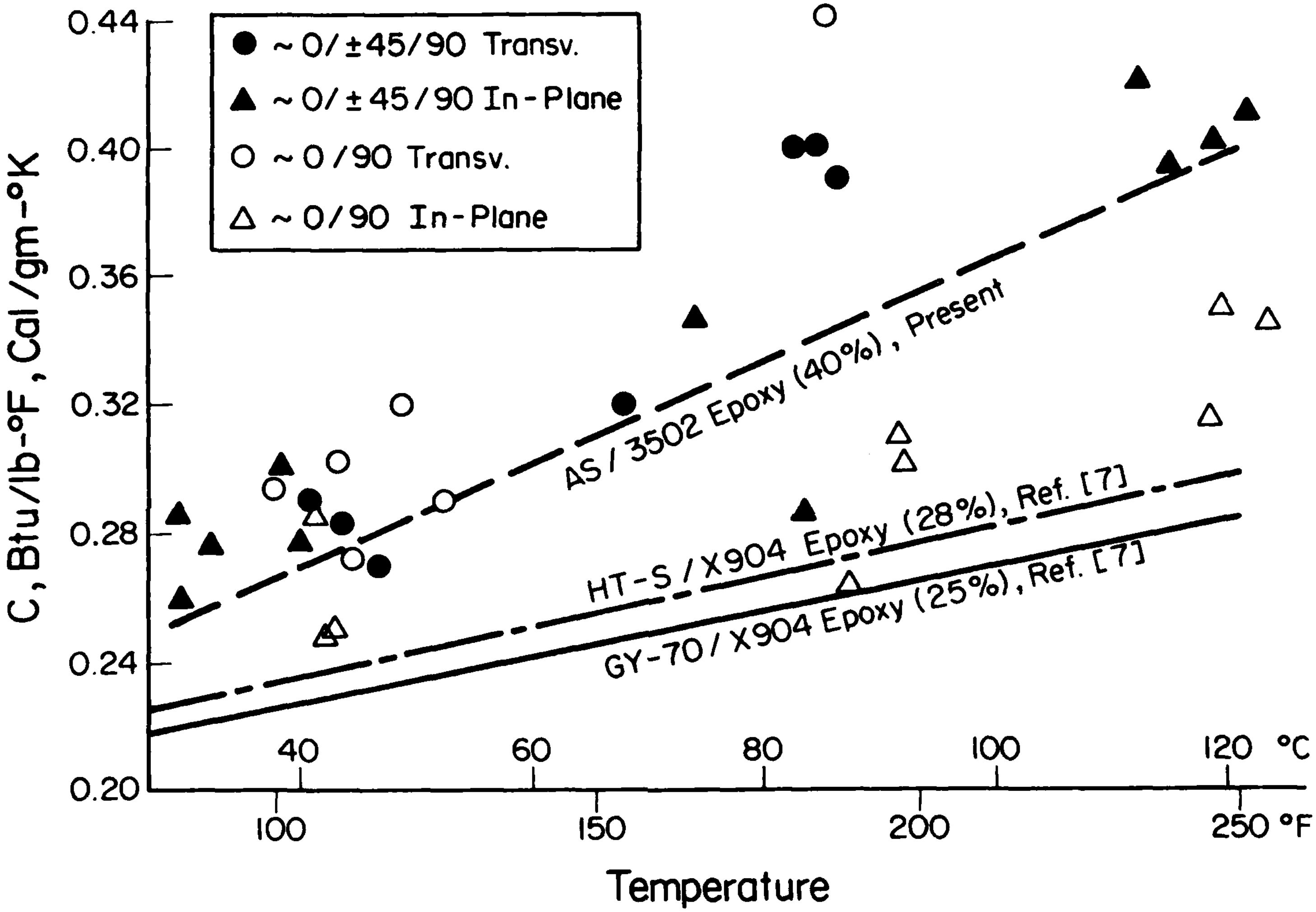

Figure A.3 Provisional Data for Specific Heat of Composites

Table A-1. Temperature-Time Record, Run No. 426

(Transverse, 0/±45/90)

Time, sec	T_1 (see note below) (°F)	T_2	T_3	T_4	T_5
0	75.3	75.3	75.3	75.3	75.5
180	82.1	76.2	75.2	75.3	75.5
360	87.0	78.8	75.3	75.3	75.5
540	91.0	81.5	75.9	75.4	75.5
660	93.2	83.2	76.3	75.4	75.5
1260	101.8	90.5	79.5	76.0	75.5
1860	108.6	96.6	83.0	77.0	75.5
2460	114.6	102.1	86.8	78.2	75.7
3060	119.5	106.7	89.9	79.1	75.3
3660	123.7	110.9	92.9	80.1	75.4
4260	127.5	114.4	95.4	81.0	75.5
4860	130.8	117.7	97.9	81.9	75.7
5460	133.7	120.6	99.9	82.3	75.1
6060	136.4	123.1	101.7	83.0	75.3
7260	140.7	127.3	104.7	84.2	75.5
7860	142.3	128.9	106.0	84.6	75.5
8460	144.0	130.4	107.2	85.2	75.7
10260	147.9	134.1	109.8	85.8	75.3
11460	149.8	135.9	111.3	86.4	75.5
13860	152.8	138.8	113.3	87.2	75.5
16260	154.7	140.5	114.7	87.6	75.4
17460	155.8	141.5	115.2	87.9	75.5
19860	156.9	142.6	116.1	88.1	75.3
20460	157.1	142.7	116.2	88.1	75.4

Notes: L=3.042 in for 6 specimen panels
T_∞ = 157.1°F, T_i = 75.3°F, θ_∞= 20460 sec
T_1, T_2 ... are chronologically the temperatures of the heating surface (x=0), three interior temperatures (x=L/6, x=L/2, x=5L/6) and the cooling plate surface (x=L).

APPENDIX B TEST SPECIMEN SPECIFICATIONS

The process of fabrication of the graphite-epoxy composite specimen was carried out under the direction of Yarcho, etc at the Structural Concepts Branch, Flight Dynamics Laboratory, WPAFB, Ohio. Because of the limited circulation of References [2] and [3]. This Appendix lists the essential characteristics of the specimens used in this study.

The "raw materials" used were Hercules AS-1/3502 low resin graphite/epoxy prepregs as were used in the specimens for Reference [1]. The plies had an average thickness of 0.0052 inches. Curing of the specimens after stacking up the necessary number of plies was carried out at full vacuum (28 in Hg) and by bringing the specimens to a temperature of 270°F at a rate of 1-5 °F/min. After a period of 45 min. at this temperature, the specimens were elevated to 350°F for 2 hours and then slowly cooled to the room temperature. The specimen panels, the finished products, had the following specifications:

TEST PANEL SPECIFICATIONS

	0/90 Composite	0/±45/90 Composite
Panel Size	6x6(±.018)in	6x6(±.016)in
Thickness, in	0.290(±.008)	0.507(±.008)
Percent (wt) Fibers	71.1	68.4
Percent (vol) Fibers	57.6 (1)	59.3
Voids, Percent	0.28	0.39
ρ lb/cu in	0.0585	0.0576
ρ_m (2) lb/cu in	0.0460	0.0461
ρ_f (2) lb/cu in	0.0660	0.0654

(1) Obtained photographically by counting the fiber area of the 0/90 composites.

(2) Computed from preceding data in each column.

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